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Engineering Education in Pre-Kindergarten through Fifth Grade: An Overview

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I. INTRODUCTION

Over the past twenty years, engineering has become increasingly recognized as a central component of the broader preschool-12th grade STEM education enterprise as well as a fundamental set of skills and mindsets for success in school and life. Fueled by field-wide motivation to be more inclusive and broaden participation in engineering (NAE, 2008; NRC, 2009a), pre-college engineering education has evolved from early university- or industry-based outreach efforts (Bottomley & Parry, 2002; Jeffers et al., 2004), to being introduced to young students through the science classroom (Fortus et al., 2004; Kolodner et al.; 2003), to being included in state and national science standards (Moore et al., 2015; Roehrig et al., 2012), to now being central to the national discussion about effective and impactful STEM education (NRC, 2014; Cunningham & Carlsen, 2016).

While much of the extant literature on pre-college engineering education has been focused on the middle and high school level, studies examining engineering in early childhood and the elementary grades have been growing rapidly in number. In a similar manner to the disciplines of science and mathematics, working with young children to cultivate early interest and understanding related to engineering is being seen as a critical pathway (English & Moore, 2018; Pattison et al., 2020b) to ultimately disrupting the persistent underrepresentation of women and BIPOC in the field (NSF, 2019). Beyond this, however, early engineering education is emerging as a fruitful approach to supporting children's overall learning and development (Gold et al., 2020), a useful anchor and catalyst for early science and mathematics learning (Cunningham, 2017; Cunningham, et al., 2020; Tank et al., 2018), and as a rich context for informal, family-based STEM learning experiences that can potentially lead to long-term interest and identity formation (Pattison et al., 2018; 2020; Pattison & Ramos Montañez, 2020; Svarovsky, Pattison, et al., 2017). As such, engineering education is positioned to play an increasing and important role in advancing the broader conversation about more meaningful, effective, and equitable STEM education.

Paper Scope and Definitions

The goal for the paper is to summarize findings from research within the field of

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engineering education with children and their families, particularly for preK-5th grade aged learners. While the broader field of engineering education has existed for over a century, much of the research until the 2000s was focused solely on engineering at the undergraduate level. Since then, there has been increasing work and focus on pre-college engineering education research, moving to younger and younger audiences until ultimately gaining traction in the past 10 years within the early childhood arena. In this paper, it should be assumed that the research and literature presented here is focused on preK-5th grade aged learners unless otherwise noted.

Pre-college engineering education for preK-5th grade aged learners tends to focus primarily on engaging in **engineering design: an intentional, iterative activity to develop an object, system, or process that addresses a particular need, solves a particular problem, or accomplishes a particular goal**. While the majority of this paper discusses engineering design education as it relates to engineering design, other aspects of pre-college engineering education are also described in order to provide a more complete representation of engineering in early childhood and the elementary grades. Some examples include: engineering decision making (including using mathematical models and optimization processes to inform engineering work) and increasing awareness, interest in, and understanding of what engineering is, what engineers do, the role of engineering in our society, who engineers are and what is important to them.

Defining engineering in a meaningful way can be a complicated task, as seen in the Engineering in K-12 Education report (NRC, 2009a) that dedicated an entire chapter to this effort. For the purposes of this paper, the definition(s) of engineering are deeply connected to the definition of the engineering design process articulated above. As such, the primary ***act of engineering*** is to engage in the engineering design process; the major focus of the ***field of engineering*** is the professional community of practice that engages in and around engineering design; and ***engineers*** are individuals who engage in engineering design.

Given the ongoing conversations between the different fields of STEM education, it is perhaps also helpful to delineate between the enterprise of engineering and that of science. While sharing many of the tools, content, procedures, and contexts with the discipline of science, engineering and science do differ in specific and important ways, with the most important difference perhaps being the **intended goals** of the work: engineering tends to be focused on designing optimal solutions to complex problems by balancing numerous tradeoffs, while science tends to be focused on discovery, inquiry, and advancing knowledge and understanding of phenomena. These complementary yet distinctly different goals then go on to shape other contours of the disciplines, such as a particular mindset, a set of practices and norms, and what constitutes warrants for claims, decisions, or actions in the given field.

It is essential, however, to acknowledge and recognize that the current disciplinary boundaries presented here, like many other aspects of education and learning, can be fluid and permeable. Most challenging, however, is that these disciplinary definitions can also be extremely problematic and inequitable, given whose voices have been privileged to contribute to and shape them - and whose voices have not been included and acknowledged. While the paper utilizes these operational definitions presented above, these equity-focused themes and challenges are revisited below, in the Essential Considerations section.

Two additional definitions that informed the structure of the paper include:

Early childhood learning settings: For the purposes of this paper, all learning contexts prior to kindergarten are considered as part of early childhood learning. This includes contexts such as preschool, pre-kindergarten programs, daycare centers, Head Start centers, community programs, and other family-based learning experiences. This decision to group all of these learning opportunities together when reviewing the literature is due in large part to the difficulty in defining "formal" and "informal" learning boundaries at these young ages, which tend to vary across state and local lines.

Formal and informal education: For educational opportunities that engage children in kindergarten through 5th grade, this paper defines learning contexts as "in-school" and "out-of-school", instead of using the terms "formal" and "informal". Typically in the literature, the term "formal education" is used to describe classroom/school-based learning, while "informal education" is used to describe learning outside of that context. However, the authors have chosen to use "in-school" and "out-of-school" as descriptors, acknowledging that the extent to which the nature of a particular learning environment can be more "formal" or "informal" varies not only by location, but also by the degree of learner choice, the types of assessment used, and the structure of the activity (NRC, 2009b).

Essential Considerations

Although we have confined the scope of the paper to research studies within the field of engineering education, it is important to recognize the many tensions and outstanding questions within this field, especially related to equity, that should be considered when interpreting findings from existing studies, including:

- The field is engaged in the deep and ongoing conversation of how engineering is defined, who decides and legitimizes these definitions, and what the implications of these definitions are for children and families, particularly from non-dominant communities and groups traditionally under-represented in engineering as a profession.
- In addition, there can be pluralistic conceptions of engineering within the field that involve both (a) "capital-E" Engineering as a Discourse (Gee, 2014) that allows some people to gain access and have political, social, and financial capital and (b) "lower-case-e" engineering as a practice that humans use to solve problems every day.
- Especially in the early childhood context, there are also questions about the boundaries, often artificially constructed, between traditional notions of engineering, other STEM domains, and broader aspects of learning and development.
- Some conceptualizations of engineering have the potential to connect with and reinforce the rich engineering-related knowledge and skills that already exist within families, while other approaches are more likely to exclude or devalue these assets, especially for families from traditionally underrepresented communities.

Additional considerations, which can be similar to challenges to other STEM education fields include:

- Engineering educators and researchers continue to encounter inequities in access to high quality engineering education opportunities and, beyond access, the fundamental inequities in the education system that privilege the learning experiences of some communities over others.

- Fundamental issues remain about who is designing, creating, and implementing engineering education studies and programs that currently exist and how different communities benefit from these efforts.
- Research from other fields, such as studies of making and tinkering or equity-oriented research in STEM more broadly, can begin to shed light on these issues. Although we do not review these literatures extensively, we highlight relevant studies as needed to provide context for findings within the engineering education literature and identify relevant connections.

In sum, even as this paper describes findings from existing literature, there is an ongoing need to problematize assumptions about engineering and engineering education, both inside and outside of school.

In the sections below, each of the Committee's questions are addressed. For clarity, the responses are organized in the following manner:

- Question 1: This response includes a review of engineering learning experiences for young children and their families up through pre-K/approximately age 5.
- Question 2: This response includes a review of engineering learning experiences for children typically in kindergarten through grade 5. We also use the "in-school" and "out-of-school" definitions for learning contexts as described above.
- Questions 3-7: Responses include perspectives for preK-5th grade aged children and settings, as appropriate.

Finally, themes outlined in the Essential Considerations section will be briefly revisited at the end of the paper in the Conclusion.

II. Committee Questions

A. Question 1: What kinds of learning experiences prior to entering school and outside of school (e.g., play-based experiences, informal interactions at home and in the community) provide children with a strong foundation for engineering learning before kindergarten?

Before children enter the K-12 formal school system, they encounter ongoing opportunities for engaging with STEM topics and practices through informal, out-of-school learning experiences with family and friends (Hurst et al., 2019; McClure et al., 2017; NRC, 2009b). These experiences are driven by young children's natural motivation to explore the physical and social world around them (NRC, 2000b, 2001) and facilitated by parents, family members, and other caring adults that are central to children's learning and development (NASEM, 2016). Important contexts for learning at this age include play with everyday objects in the home (Cook et al., 2011; Galindo et al., 2019; Gomes & Fleer, 2019; Vandermaas-Peeler, Mischka, et al., 2019), exploration of nature and the outdoors (Eberbach & Crowley, 2017; Vandermaas-Peeler, Dean, et al., 2019; Zimmerman & McClain, 2016), conversations with family members and other significant adults (Callanan et al., 2012; Dou et al., 2019; Hurst et al., 2019), shared reading and oral story telling (Anderson et al., 2005; Pattison, Svarovsky, & Ramos Montañez, 2020; Shirefley et al., 2020); experiences with designed educational environments and tools, such as museum exhibits and media (Callanan, Legare, et al., 2020; NRC, 2009b); and close observation of and participation in adult activities (Rogoff, 2014; Rogoff et al., 2003; Son & Hur, 2020). During these experiences, young children develop their STEM-related skills and knowledge through observation, experimentation, problem-solving, and curiosity questions (Callanan, Legare, et al., 2020; McClure et al., 2017; NRC, 2001; Renninger, 2007). In turn, adults model skills and practices, provide explanations, guide and scaffold children's exploration, and provide new learning resources and experiences based on their children's evolving interests and abilities (Callanan, Legare, et al., 2020; Crowley et al., 2001; NASEM, 2016; Takeuchi et al., 2019; Vandermaas-Peeler, Mischka, et al., 2019).

Developmental Perspectives on Engineering During Early Childhood

Henry Petroski, a well-known professor of civil engineering and author of several books about engineering and design, once famously wrote, "Children are born engineers," when asked to describe the natural tendencies of young learners to explore, create, and play (Petroski, 2003). A number of studies have investigated what engaging in engineering activity looks like for very young children between the ages of 3-5. Early studies sought to identify pre-cursors to engineering thinking by observing block-based play (Brophy & Evangelou, 2007; Bagiati, 2011; Bagiati & Evangelou, 2011). Bairaktarova and colleagues (2011) observed engineering behaviors such as asking questions, setting design goals, and evaluating designs within pre-school children at different center stations, including a sensory table filled with sand and water, a drawing and painting station, and a puzzle center. Gold and colleagues (2017) developed the Preschool Engineering Play Behaviors observation instrument (P-EPB) and used the tool to examine associations between engineering play and mathematical skills and knowledge as well as spatial skills (Gold et al., 2020).

In addition to studies that have focused explicitly on informal, out-of-school engineering learning before children enter kindergarten, research in the fields of mathematics and science suggest that children this age are capable of engaging deeply with engineering practices and developing the foundations of engineering mindsets (Keifert & Stevens, 2019; NRC, 2005, 2007; Shwe Hadani & Rood, 2018; Zimmerman & Klahr, 2018). The last several decades of cognition and development research have largely dispelled the deficit-based belief that before a certain age or developmental stage, young children are not capable of engaging deeply with STEM-related knowledge or practices - and that children are especially able to access these ideas and skills with adult guidance and attention to age-appropriate supports (NRC, 2005, 2007). Preschool-age children are capable of, at least at a foundational level, many of the reasoning skills underlying engineering design thinking, such as identifying relational and causal patterns, categorization, deductive and inductive reasoning, generating questions, foundational modeling skills such as the appreciation of representational qualities of objects and images, use of problem-solving heuristics, experimentation, and reasoning about evidence (Bjorklund & Causey, 2018; Klahr et al., 2011; NRC, 2007; Shwe Hadani & Rood, 2018; Zimmerman & Klahr, 2018). By this age, children are also increasingly sophisticated problem-solvers. For example, by the age of two children are better at developing questions, maintaining focus on a goal, monitoring their progress, making corrections, and evaluating results (Bjorklund & Causey, 2018; Zimmerman & Klahr, 2018). Children this age are also developing an ever-deepening awareness of the thinking and beliefs of others, allowing them to infer and interpret goals and intentions of individuals and practice empathy (IOM & NRC, 2012; NRC, 2000a, 2007).

Despite the strong potential for engaging preschool-age children in engineering design, it is important to keep in mind that children this age are still developing their skills and capacities in a number of areas relevant to engineering. Although there is considerable variation across children, important developmental domains at this age include (a) executive function, self-regulation, and planning capacities; (b) socioemotional learning and ability to manage emotions associated with challenge and failure; (c) metacognition and children's awareness and ability to articulate and actively manage their own reasoning and learning processes; (d) and fine motor skills for manipulating materials and realizing designs to solve engineering challenges (Bjorklund & Causey, 2018; Mudrick et al., 2020; NRC, 2000a; Zimmerman & Klahr, 2018). For example, engaging in the engineering design process requires children to practice planning and managing a series of interrelated, goal-oriented tasks (NASEM, 2020). These cognitive skills are the foundation of executive function, which continues to develop throughout childhood (Blair, 2016; Diamond, 2013). Given this, adult support is often critical for helping young children engage with engineering design.

Adult-child and Family-based Interactions During Engineering Activity

Adult guidance and scaffolding, familiar and age-appropriate program contexts, and opportunities to engage with reasoning that does not rely on verbal capabilities are all approaches that have been shown to help young children engage successfully with science and math at this age. Parents and other adults can model and scaffold learning strategies and metacognition that preschool-aged children can then apply to current and future problem-solving tasks (Bjorklund & Causey, 2018; Vandermaas-Peeler, Mischka, et al., 2019), such as asking "constraint-seeking" questions (Legare et al., 2013); planning and strategizing (Hudson & Fivush, 1991); and using evidence to reason and make design decisions (Bjorklund & Causey, 2018). Children's problem-solving can also be greatly improved when the problem and problem context are familiar and make sense to them (Bjorklund & Causey, 2018; NRC, 2007; Zimmerman & Klahr, 2018), such as story-based or creative play activities (Bairaktarova et al., 2011), and when children have opportunities to demonstrate and test their reasoning with age-appropriate materials without relying solely on verbal communication (NRC, 2007). At a larger time scale, initial evidence suggests that adult support is also important for recognizing and valuing children's emerging interests related to engineering design, connecting these interests to existing family values and practices, and seeking out new opportunities to support these interests (Alexander et al., 2012; Pattison, Svarovsky, Ramos Montañez, et al., 2020; Pattison & Ramos Montañez, 2020).

A number of studies have focused specifically on parent-child interactions during engineering activities. Svarovsky, Cardella, et al. (2017) explored young girls aged 3-5 engaging in a range of engineering activities with a parent during a museum-based drop-in program. Their analysis suggested that these family groups demonstrated engineering behaviors such as problem scoping, idea generation, and design evaluation during the design activities (Cardella, Svarovsky, & Dorie, 2013; Dorie, Cardella, & Svarovsky, 2014; 2015). In addition, mothers and fathers interacted differently with their daughters, with mothers asking more guiding questions than fathers, and fathers being more directive than mothers included in the sample (Svarovsky, Cardella, et al., 2017). Dorie and Cardella (2011) also studied conceptions of engineering within children's books as part of a larger study that focused on parent-child interactions while reading engineering-focused storybooks (Dorie Brinkman 2015; Dorie & Cardella, 2015).

Early interest development related to engineering for young children involves the whole family (Pattison et al., 2016, 2018). Parental beliefs, awareness, and interests evolve in parallel with those of their children and play an important role in influencing subsequent engineering-related learning experiences. Early childhood engineering programs, such as *Head Start on Engineering*, can foster long-term engagement and interest development related to engineering for children and their families (Pattison et al., 2020; Svarovsky, Pattison, et al., 2017). These interests vary greatly across families and often connect to engineering and program elements in unique and unexpected ways, based on the values, prior interests, and life experiences of each family (Pattison et al., 2020). These programs can also have important, long-term impacts for early childhood educators, including broadened understanding of engineering and a problem-solving process, confidence engaging families with engineering activities and frequency incorporating engineering into the classroom (Pattison et al., 2018).

Connecting the engineering design process to families' everyday problem solving appears to be a powerful way to make engineering relevant for families with young children, broaden awareness about what engineering is, build on families' existing engineering-related knowledge and practices, and foster ongoing motivation to engage with engineering. Spanish- and English-speaking families from low-income communities find resourceful ways to integrate engineering into ongoing family learning experiences despite challenges. Important barriers these families face include lack of engineering-related learning experiences, costs associated with existing programs and resources, life challenges connected with poverty, and racism and cultural barriers within the education system. Promising considerations for developing early childhood family-based engineering activities and engaging families and early childhood educators in this process include: (1) embedding the engineering challenges within a compelling, age-appropriate story or context to motive the design process; (2) clearly articulating the design goals, criteria for success, and constraints; (3) carefully selecting materials that are engaging, age-appropriate, and afford creative design solutions; and (4) identifying ways the engineering activity supports other aspects of child and family development that are important for families and educators (Pattison et al., 2018; 2019; 2020).

Finally, when considering the ways that early informal learning experiences support engineering learning before kindergarten, we note two common assumptions that have the potential to undermine efforts to achieve more equitable engineering education for all communities. The first assumption is that approaches to learning in early childhood are similar across cultures. For example, play is often cited as one of the most effective approaches to supporting STEM learning at this age (e.g., Yogman et al., 2018). However, play is not a concept that is universally shared or valued across communities (Gaskins, 2008; Rogoff, 2014; Shirilla & Golinkoff, 2019), and research suggests that other approaches may be equally if not more effective for supporting children's learning and development in other cultural contexts (Alcalá et al., 2018; Wang et al., 2020). This is not to suggest that play is not a promising context for engaging young children and their families in engineering design and supporting the development of engineering design thinking skills and habits of mind for some families (e.g., Bairaktarova et al., 2011; Gold et al., 2020; Tõugu et al., 2017). However, for many families and cultural communities, play may not be as relevant or as valued a learning context. More research is needed to explore opportunities for engineering learning connected with other types of early childhood and family learning approaches, such as everyday conversations between adults and children (Callanan et al., 2012; Solis & Callanan, 2016), participation in and close observation by children of adult activities (Rogoff, 2014; Rogoff et al., 2003), and storytelling and narrative-based learning (Melzi et al., 2013; Shirefley et al., 2020).

The second assumption is that families from certain communities are deficient in their STEM knowledge and practices, and thus children in these families must receive remediation in order to be successful in school (e.g., Heckman, 2012). This assumption is often based on normative expectations and beliefs about what learning and teaching look like in Western, White, middle-class families. In contrast, numerous studies have documented the rich STEM-related knowledge, skills, and practices within families from other cultural communities (Callanan, Solis, et al., 2020; Gutiérrez, 2018; Mejia et al., 2018; Siegel et al., 2007; Solis & Callanan, 2016), highlighting the need for educators to better understand, connect with, and build on these funds of knowledge (González et al., 2005) to not only support more equitable STEM education but also expand and enrich conceptualizations of STEM more broadly. For example, preschool classroom teachers can engage parents as partners in developing and implementing activities that center family knowledge and experiences (McWayne et al., 2018).

Engineering in Pre-Kindergarten Classrooms

Curriculum packages for pre-kindergarten classrooms have only recently been in development. Most notable is the Wee Engineer curriculum, developed as part of the Engineering is Elementary curriculum series (Cunningham et al.,, 2018). Using a simplified three-step engineering design process, Explore-Create-Improve, Wee Engineer units provide pre-kindergarten educators and students with a meaningful design context, a clear design challenge, simple materials to explore and use for design solutions, and connections to imaginative play. For example, in one Wee Engineer unit, children are introduced to the design challenge of building a basket through the use of a puppet and a marginally functional basket that provides an initial frame for the design work. Children then explore materials at will during open play before sharing ideas for different designs. Finally, children build their design ideas, test them, and continue to play, build, and iterate (Cunningham et al., 2018). Wee Engineer is built on the foundational elements of the Engineering is Elementary curriculum, described in more detail below in Box 3.

In addition to engineering curriculum, new observation protocols connected to engineering and specifically intended for pre-kindergarten classrooms are being developed to help assess the engineering learning and engagement of young children. Bagiati & Evangelou (2018) have been developing the Pre-Kindergarten Engineering Observation Protocol (PREEOP), which includes STEM knowledge, STEM skills, and STEM dispositions. PREEOP also includes an observation rubric for STEM feelings, which speak to emotional/affective reactions (such as enthusiasm, boredom, and pride of self-achievement) experienced during engineering activities. Other observation tools for early childhood engineering focus on the development of engineering habits of mind, such as systems thinking, creativity, optimism, and collaboration (Lippard et al;. 2018; Van Meeteren, 2018).

B. Question 2: What are the promising approaches for integrating engineering practices in K-5th grade formal and informal education? What kinds of learning experiences support children in developing an understanding of the epistemic underpinnings of engineering?

Currently, there exist a wide range of approaches to engaging children in K-5th grade in learning about engineering and engaging in meaningful engineering activities, such as leveraging connections between engineering, science, math, and technology; providing opportunities for children to participate in engineering design activities and collaboration; and increasing exposure through media, products, and local communities and networks. Approaches range from short stand-alone activities often lasting less than an hour to multi-day curriculum units or multi-session weekend, after school, or summer programs. Children learn about engineering and learn engineering-related skills through school-based as well as out-of-school activities at home and in their communities. Many different people can participate in supporting children as they develop engineering knowledge and skills, including: teachers, parents, other family members, facilitators at science centers/museums, undergraduate/graduate students/faculty from universities, and practicing engineers.

A Focus on Technology and Introducing the Work of Engineers

Some short activities focus on introducing engineering and the work of engineers in relationship to technology -- in the world around us, objects can be naturally occurring or designed by people. In this approach, objects designed by people are examples of technology, and the work of designing those technologies is engineering work. Engineers, then, are people who design technologies (including everyday objects like pencils) to solve problems or meet needs. Typically this approach involves children identifying objects in their own classrooms or in their own homes to consider whether those objects are examples of technology. This can allow children to center objects that are meaningful or interesting to them as they think and talk about engineering work and the types of things engineers design, test and redesign. However, a limitation of this approach is a focus on objects or products, while some engineering work focuses on developing processes. Activities that allow children to investigate different specific engineering disciplines can help children to recognize that engineering work also involves processes or other innovations beyond everyday objects. These activities also can help children recognize the breadth of engineering work -- i.e. that engineers do more than designing cars and bridges (and everyday objects). While a major focus of these activities is raising awareness of engineering as a profession, these activities also introduce the idea of design being a central part of engineering work.

A Focus on Engineering Design

Many approaches to K-5th grade engineering education-- across in-school and out-of-school settings-- focus on engineering design: explicitly teaching specific design skills; explicitly teaching an engineering design process; and/or providing opportunities for children to engage in an open-ended design challenge. While there are many different models of the engineering design process, most models represent design as a set of three or more activities that are part of an iterative process. This is similar to the ways that design is theorized, studied, and taught to undergraduates, graduate students, and professionals. For example, Atman and her colleagues summarize three major stages of design: problem scoping, developing alternative solutions, and project realization (Atman et al., 2007). These three stages are similar to the three main activities of engineering design in the Next Generation Science Standards and the Framework for K-12

Science Education: “define”, “develop solutions”, and “optimize” (NGSS Lead States 2013; NRC 2012). Other models and representations of the engineering design process typically include these three main activities too, but often by presenting the more nuanced set of activities that make up those major phases, such as in the design process presented in Figure 1.

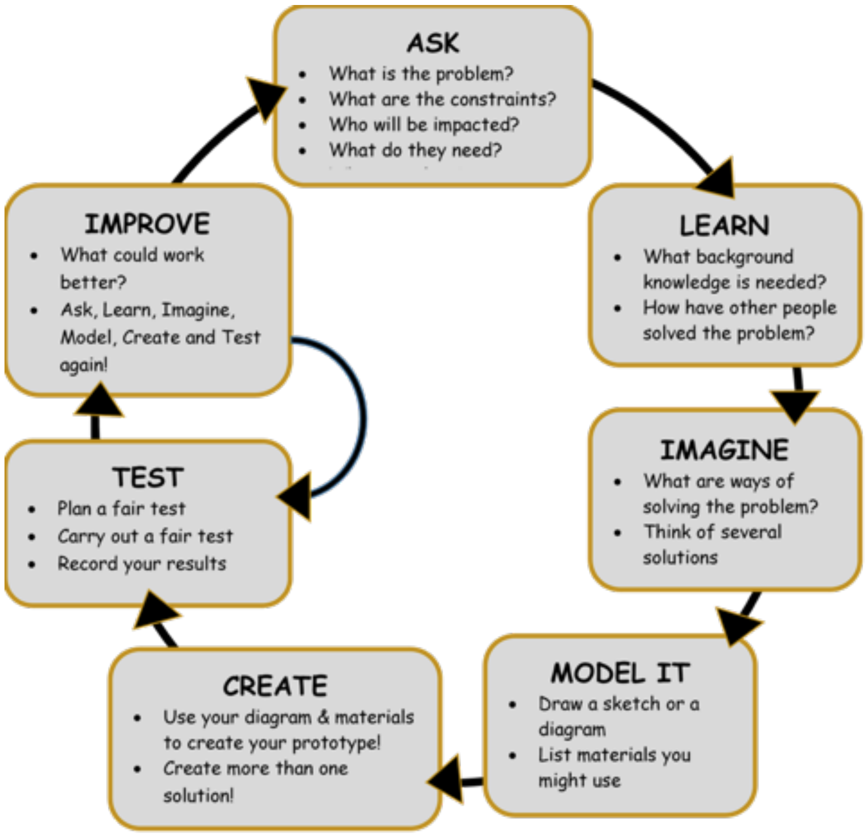

Figure 1: Design Process Model Developed for the National Society of Black Engineers “Summer Engineering Experiences for Kids” Program for 3rd-5th Grade Aged Children

Engineering Design: Idea Generation and Idea Fluency

Often engineering and engineering design are thought of as “problem solving” or approaches to “out-of-the-box thinking.” Skills and practices that children develop that are related to the second two phases of design, developing alternative solutions and project realization/optimization, align with these areas of emphasis. Research has shown that undergraduates and adults can tend to become “fixated” on an initial solution idea, where designers focus on making the initial idea work even after identifying flaws or weaknesses with that approach rather than exploring alternative solutions (e.g. Ullman, et al., 1998). Some early research suggests that children can also become fixated on initial solution ideas if they have not developed skills or practices that lead to more extensive solutions exploration, or if they have not been given feedback or guidance to explore alternative solutions (Cardella, 2019). Approaches to teaching idea generation or idea fluency (Crismond & Adams, 2012) to K-5th grade aged children often focus on encouraging or requiring children to draw and/or describe multiple possible solutions before they are able to begin building or making a prototype of their solution. Idea generation is also sometimes associated with creativity and generating creative solutions. In her dissertation work, Hegedus (2014) investigated ways that fifth graders worked individually and collaboratively to generate creative solutions, and found that creativity was culturally produced in the classroom through idea generation as well as through design and innovation, gumption/resourcefulness, and social value.

Engineering Design: Problem Scoping and Centering People

Another important aspect of engineering design is that it is a process of not only solving problems, but also a process of identifying and understanding problems. Too often engineering learning experiences emphasize problem solving without making space for children to engage in processes of identifying problems to be solved; identifying criteria and constraints; gathering more information to learn about the problem; and/or redefining the problem. Rather than allow children to engage in the work of "problem scoping" (Watkins et al., 2014; Atman et al., 2007; Schön, 1983) curricula and activities present problems that are already well-defined. In other cases the teacher or activity facilitator acknowledges that problem scoping is part of the engineering design process, but then does the work of problem scoping for the child. Sometimes it is important for teachers and activity leaders to model this process for the learners, but it is important that children also have opportunities to do this, for several reasons: (1) children tend to ask many questions, but there is little time during the school day for children to engage in question asking; practicing problem scoping can make space for children to engage in question-asking, (2) engagement in problem scoping can help designers (including children) to identity creative solutions, and (3) problem scoping and problem framing involve skills that need to be developed and practiced. Research at the undergraduate level has recognized problem scoping ability to be a major difference between undergraduates and practitioners (Atman et al., 2007), where practitioners spend significantly more time with problem scoping than do undergraduates. Recent research has similarly found that when given opportunities to engage in problem scoping, there is variation in how children frame the problem, particularly in terms of trying to meet the expectations of the teacher vs. trying to understand the needs of the fictional client, and that practicing empathy can help children focus on the needs of the fictional client (McCormick & Hammer, 2016). Watkins and her colleagues provide further insights into the ways that children engage in problem scoping by attending to children's opportunities to name, set the context, and reflect (Watkins et al., 2014).

Approaches to introducing and integrating engineering to the K-5 classroom also vary in terms of the extent to which engineering and engineering design are human-centered or user-centered. Approaches that emphasize clients, users, stakeholders, or other people (or animals, particularly for preK-2) that might benefit or be impacted by the outcome of the engineering design work can make space for children to engage in problem scoping while also positioning engineering as a field and a human activity that is centered around people, their needs, and their problems (Hynes & Swenson, 2013; Zoltowski et al., 2012; NAE, 2008). However, many activities still position engineering and engineering design as being focused on the "thing" that is designed -- whether a bridge, tower, or another product.

Box 1 shows an example of an activity that is initially framed as a build challenge. The focus is on building a tower, with a team, with the materials that have been provided, within a certain amount of time. The revised version of the activity adds a context to the activity as well as some additional prompts related to problem scoping (e.g. "Think about questions you can ask your mentors to learn more about this challenge!"). In the revised version, the activity is shifted to a particular setting, with implicit groups of people who will have specific needs and could benefit from the design artifact in particular ways. Additionally, some of the key information about constraints of the activity have been removed -- rather than stating up front that children have 30 minutes to complete the task and that a successful model of a tower must be free-standing and constructed on top of a flat surface, the activity is presented as ill-defined (i.e. without all of the information needed) and children are encouraged to ask questions to identify the additional constraints. By encouraging children to ask questions to identify the additional constraints, the revised activity provides opportunity for children to engage in problem scoping activities. This shift in the way the activity is presented aligns with the work of engineering design practice, where problems are generally ill-defined (Jonassen et al., 2006) but also communicates that asking questions is an important part of engineering design work.

Box 1. Sample Engineering Activity, Without and With Context and Opportunities for Problem Scoping

ORIGINAL ACTIVITY: Tallest Tower Challenge

Objective: Using only the materials provided to your team, please design and build the tallest tower in 30 minutes.

Challenge Rules:

- You must use only the materials provided for the challenge.
- The tower must be free-standing, and it must be constructed on top of the table (or another flat surface).
- Your goal is to build the tallest tower with the materials provided.
- You may want to sketch some ideas before you begin.
- There are many different ways to complete this challenge. Be creative!

REVISED ACTIVITY: Playground Tower Challenge

Objective: Using only the materials provided to your team, please design and build a model of a tower that could be added to a playground at your school.

Challenge Rules

- You may use only the materials provided for the challenge.
- Your goal is to build a model of a tower with the materials provided.
- Remember, the tower model you are creating is for a tower that would be added to a playground at your school.
- You may want to sketch some ideas before you begin.
- There are many different ways to complete this challenge. Be creative!
- Think about questions you can ask your mentors to learn more about this challenge!

Challenge Rules (not included in Student Manual – for Leaders only)

- You have 30 minutes to complete the challenge.

- The tower must be free-standing and it must be constructed on top of the table (or another flat surface).
- Materials that students can use include…

A second example of revising an activity to provide more opportunities for children to engage in problem scoping is presented in Box 2. In the original activity, children are directed to build a table out of newspaper tubes. There are multiple ways that children can create solutions, so the problem is open-ended. However, all of the “rules” are provided, so the problem is well-defined and there is not opportunity for children to ask questions to better understand the problem. Children are also not encouraged to consider who might use the table. In the revised version, children are encouraged to first think about the larger context of how paper is used, and how they use and dispose of paper themselves. When they are asked to think about what else they might do with paper after they are finished with it, and they are asked to consider family members or other people, they are encouraged to engage in the process of identifying problems and identifying people’s needs (two aspects of problem scoping). They are then asked to think specifically about designing a table out of paper (the facilitator could instead allow children to create any of the ides children have come up with; however, shifting the focus to paper tables could be more manageable for a large group setting or if the facilitator has limited prior experience with facilitating engineering design experiences), and prompted to think about what questions they have. This allows them to engage in information gathering (another aspect of problem scoping) and allows children to participate in the process of identifying constraints (another aspect of problem scoping).

Box 2. Sample Engineering Activity, Without and With Context and Opportunities for Problem Scoping

ORIGINAL ACTIVITY: Paper Table

Objective: Design and build a table out of newspaper tubes. Make it at least eight inches tall and strong enough to hold a heavy book.

Challenge Rules:
- You must use only materials provided
- The table must be free-standing, and it must be constructed on top of the table (or another flat surface)
- There are many different ways to complete this challenge.
- Be creative!

Materials:
- 1 piece of cardboard or chipboard
- Heavy book

- Masking tape
- 8 sheets of newspaper

REVISED ACTIVITY: Upcycling Design Challenge

Introduction: How do you use paper? What do you do with paper at home? What do you do with paper when you are done?

Challenge: What else can you do with paper after you are finished with it?

After children suggest many different options, then: Can you think of anything that you can make with paper that might help your mom, your dad, your brother or sister, or anyone else you know?

After children suggest many different options, then: Did you know that people have also used paper and cardboard to create furniture?

After children have an opportunity to respond (with possible follow-up facilitation): Let's try to make something out of paper today. You will work in a team to create a paper table.

What questions do you have?

Questions that children typically ask:

- *What materials can we use? 1 piece of cardboard, 8 sheets of newspaper, 12 inches of masking tape)*
- *Can we use any other materials? No (although facilitators may choose to allow other materials)*
- *How much time do we have? 30 minutes*
- *How tall does it need to be? At least 8 inches tall*
- *How much (weight) does it need to hold? At least one heavy book*
- *Does it need to be all one piece? No*
- *Does it need to have legs? No*

Debrief: What did you do while you were working on this activity? *(capture verbs on a whiteboard or another shared space. After children are done sharing verbs, talk about how teach verb relates to the different elements of the engineering design process)*

Who did you design your table for? How did you design your table for that person? (*this question can also be asked while groups are working*)

Engineering Design: Importance of Narratives and Story

In the example in Box 1, a context is included in the activity through a brief narrative: "please design and build a model of a tower that could be added to a playground at your school." However, another promising approach to introducing contexts, clients, users and stakeholders through narratives is through the use of storybooks. Connecting storybooks with engineering design is a promising approach for introducing a client/user and allowing children to participate in the process of problem scoping, where information from the book (and possibly other sources) can help refine the problem definition. This approach is also promising for two other reasons: (1) it recognizes the constraint that impacts many elementary school classrooms, where a certain amount of time each day needs to be devoted to reading, and (2) it makes space for children who love to read to now engage in engineering while also providing opportunities for children who enjoy engineering and design projects to engage in reading. Novel Engineering, discussed below in Box 4, is one approach for integrating engineering and excellent children's literature for grades K-5 created at the Center for Engineering Education Outreach at Tufts University.

Engineering Design: Writing Connections

Engineering design can also be synergistic with literacy activities focused on writing. In creating and keeping engineering notebooks, children can practice their writing skills while also participating in and practicing engineering discourse. In their development of an engineering notebooking tool, Wendell and Andrews (2017) developed distributed scaffolding that complements classroom structures and practice in order to support children in thinking and writing about their understanding of the problem, findings from their tests, and their final designs. In an early study of the engineering notebooking tool, Wendell and Andrews found that the notebooking tool initially did not support students' engagement in design largely because the classroom culture did not value taking time for documentation and reflection, but during final oral share-outs of project work and a final writing task, the notebook tool supported students' engineering design practices and disciplinary discourse (2017). Similarly, in another study, Hertel and his colleagues (2016) found that engineering notebooks can scaffold student design activity (by structuring teachers' lessons, providing references for student decision making and consensus, providing prompts for students and groups to refocus their activity, focusing student attention on relevant details and processes and previewing future parts of the lesson and design process) and support epistemic practices of engineering (by prompting students to synthesize and reflect on engineering design, providing a record of testing information for design evaluation and improvement planning, supporting communication of ideas to other students and to the teacher, providing visual reference for development of explanations, and holding students accountable to plans). Other research has demonstrated that engineering notebooks can provide opportunities for children to reflect on their engineering practices and reflect on their understanding of what design is and that engineering notebooks can allow teachers to assess and provide feedback on students' understanding of design (Douglas et al., 2018).

Engineering Design: an Iterative Process Involving Testing and Improving

Another core aspect of engineering design is the process of creating prototypes that are iteratively created, tested, and revised. Part of the nature of engineering design work is that there is not a single correct solution, or even a single "right" type of solution, but instead designers consider many possible solutions and weigh the trade-offs between the possible solutions (e.g. Kafai et al., 2014; Purzer et al., 2013). This open-endedness also leaves space for children to choose to try things that might not work -- while the iterative process of testing, learning from testing, and revising makes space for children to experience failure as a constructive process (e.g. Martin, 2015; Litts et al., 2016; Lottero-Perdue, 2015; Lottero-Perdue & Parry, 2017). However, many researchers also recognize that some learning contexts do not value or make space for these failure moments and the ways children experience failure may differ. Creating space for failure and iteration may be particularly challenging for youth from marginalized communities who "attend schools in which missteps of any kind are likely not to be tolerated" (Bevan et al., 2017, p. 2) or who experience engineering learning environments as "spaces for risk management" (Wright et al., 2018). Further, because some students and schools have been labeled as "failures" the term carries additional negative connotations for some learners (Ryoo et al., 2015, as cited in Vossoughi et al., 2016). Additionally, some researchers caution against associating failure with iteration, since any design can be improved through an iterative design process, not just those design solutions that do not work.

Engineering Design and Epistemic Practices

While the engineering design process and practices associated with the Next Generation Science Standards are an important area of focus for preK-5th grade engineering education, this focus is often not sufficient for supporting young learners in developing an understanding of the epistemic underpinnings of engineering. Engineering epistemology work by Cunningham and others, which is still connected to engaging young learners in engineering design, highlights key differences in deep disciplinary practice in engineering and the definition/representation of engineering within NGSS. For example, Cunningham and Kelly (2017) note that "For typical engineering design challenges in professional and educational settings, the designer engages in epistemic practices, employs crosscutting concepts (such as systems thinking and scale and proportion), and draws in relevant knowledge as required by the tasks at hand (e.g., knowledge of materials, structures, electronics)." (p. 499). As engineering is integrated with science, math, and computational thinking, as well as with language arts and other subjects, children can begin to develop these epistemic practices.

STEM Integration

Another approach for bringing engineering into the early grades is known as STEM Integration or Integrated STEM, which suggests that engineering can be a fruitful and productive pathway to developing disciplinary skills and knowledge in science and math, particularly through the engineering design of solutions and/or technologies (Bryan et al., 2015; NRC, 2014). This approach is quite authentic to professional engineering practice, where engineering work such as design, analysis, and optimization is often informed by data, mathematical models, and scientific principles. The degree to which a learning experience is considered to be integrated can vary depending on a number of variables, such as the goals and context of the experience, the role of the teacher, the connections between the different disciplines, and the type and scope of assessments used (Vasquez et al., 2013). Examples of integrated STEM curriculum include Engineering is Elementary, Novel Engineering, and PictureSTEM, outlined in Boxes 3, 4, and 5 below.

<u>Box 3. Engineering is Elementary</u>

One of the most commonly used and referenced curriculum packages for 1st through 5th grade classrooms is Engineering is Elementary (EiE), which began in 2003 as a curriculum project at the Museum of Science in Boston. Focused on introducing engineering to young learners, EiE developed 20 individual units that each focused on a different type of engineering, such as structural engineering, biomechanical engineering, and package engineering. A four-lesson framework provides common structure across the set of units, which reflects intentional connections to other domains and disciplines:

- Lesson 1 integrates engineering with literacy and begins with an illustrated storybook that presents a rich narrative, often situated in different areas of the world, in order to provide context for the unit and ultimately the design challenge to be addressed by the students.

- Lesson 2 provides an introduction to a particular sub-field (or type) of engineering and an expository activity connected to science or engineering concepts relevant to the design challenge.

- Lesson 3 often integrates engineering with science content and practice, typically featuring an exploration of phenomena, materials, or other systems that will inform the designs students create, and typically involves data collection and analysis. Lesson 3 can sometimes also include connections to mathematical content standards such as operations and algebraic thinking and measurement and data.

- Lesson 4 builds on the prior three lessons by presenting students with a clear engineering design challenge connected to the original story in Lesson 1, authentic design problems from the sub-field described in Lesson 2, and knowledge and data gained during Lesson 3. During Lesson 4, students engage in each step of the five-step EiE engineering design process as seen in Figure 2, often drawing on content and practices from science and mathematics.

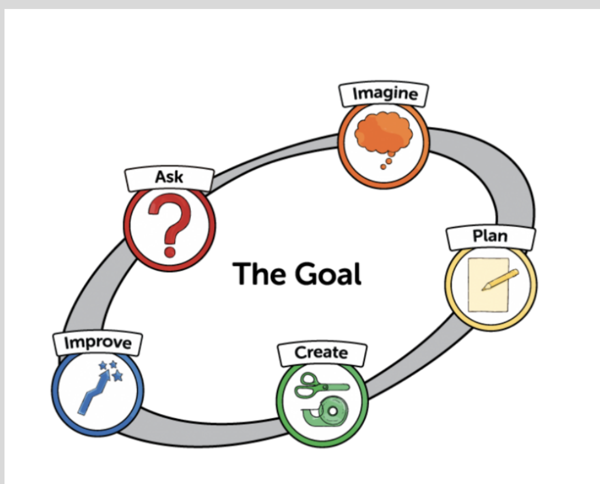

Figure 2. EiE Engineering Design Process

Each unit has been mapped to Next Generation Science Standards, ITEEA Standards for Technological Literacy, Common Core Math Standards, and Common Core English Language Arts Standards, emphasizing the integrated approach of EiE. Every unit also includes two introductory lessons which focus on helping students develop a foundational understanding of both engineering and technology. Commonly, teachers engage students in these introductory lessons once before an initial EiE unit in their classrooms and do not repeat them if additional EiE units are presented.

From its inception, EiE utilized extensive field testing and evaluation work to develop its products (see, for example, Lachapelle, 2008; Lachapelle et al., 2011; Higgins et al., 2015; Cunningham et al., 2018), and has been the focus of a number of research studies (e.g. Lottero-Perdue & Parry, 2017; Wendell, Wright, & Paugh, 2017). An efficacy study (Cunningham et al., 2020) funded by the National Science Foundation has also shown that students who engaged in EiE had greater learning gains in both engineering and science than students who had engaged in a control curriculum. In addition, females had larger learning gains in engineering than males.

Recognizing the significant need for professional development of elementary teachers in order to prepare them to implement engineering in their classrooms, EiE also created an impressive professional development effort, including cultivating a national network of certified PD providers and an extensive video and resource library that included examples of each lesson for each of the 20 original units. In 2017, EiE reported reaching over 14 million students with its products (Cunnignham, 2017), and its curriculum series has expanded in recent years to include EiE for Kindergarten, a pre-kindergarten curriculum called Wee Engineer, and several products intended for use in informal learning settings such as afterschool clubs (the Engineering Adventures and Engineering Everywhere series) and the home (EiE Families).

Box 4. Novel Engineering

Novel Engineering is an approach that invites teachers and students to engage in the practices of engineering design while drawing on the contexts and narrative found in pieces of excellent children's literature. Within Novel Engineering units, teachers and students begin by reading a text, such as *The Snowy Day* by Ezra Jack Keats, and then engage in a discussion to identify situated problems faced by the characters in the story. Once the class agrees on a problem to attempt to solve with engineering, the students engage in problem scoping using what they know and can infer from the story, and then conceptualize a design to solve the problem. Then the students test their designs, gather feedback, and refine and test their designs once again, before sharing out their final work with each other.

Novel Engineering units are mapped to NGSS and Common Core ELA standards, highlighting the deep integration of these two areas within this approach. Evaluation studies have shown that students engage in science practices such as making inferences and predictions, using evidence, and analyzing data while engaging in different steps of the design process. In addition, students also participate in close reading, analyzing text, writing, and other forms of communication throughout the Novel Engineering arc (Portsmore & Milito, 2018). Research on teachers implementing Novel Engineering suggests that while teachers can be comfortable engaging in some aspects of engineering design, they may often benefit from professional development focused on specific areas of the design process, such as problem scoping and the interpretation of feedback after testing designs (Wendell et al., 2014).

Box 5. PictureSTEM

PictureSTEM is an integrated STEM+C curriculum that uses engineering as the anchoring frame that weaves together - and promotes the learning of - concepts and practices from science, mathematics, and literacy for students in grades K-2 (Tank et al., 2018). The design process used in the PictureSTEM units, as seen in Figure 3, explicitly names a "Learn" step that is sometimes included within the broader category of problem scoping.

The emphasis on the "Learn" step is seen in the structure of the PictureSTEM units, which often begin with an introduction to engineering and the design context (the Define step), move into three or four lessons that connect the exploration of science, mathematics, and computer science content and practice with works of children's literature (the Learn step), and then conclude with two lessons dedicated to the Plan, Try, Test, and Decide steps of the engineering design process. For example, in the Designing Toy Box Organizers unit, lessons 1-4 tie children's books to the practice of computational programming, the mathematical concept of a standard unit of measurement, and the science content and practice of investigating properties of materials. Lessons 5 and 6 invite students to use what they have learned in lessons 1-4 to design, build, and test a toy box organizer for their fictional client.

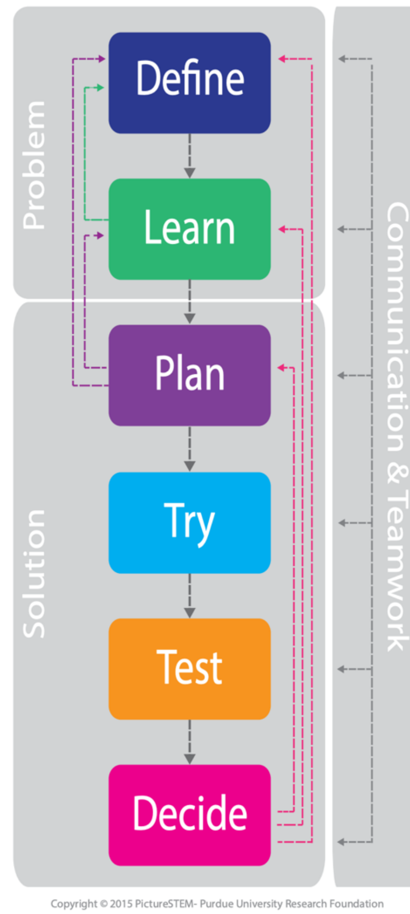

Figure 3. PictureSTEM EDP

PictureSTEM units are mapped to Next Generation Science Standards, Common Core Mathematics Standards, Common Core English Language Arts Standards, and Computer Science Teachers Association Standards. In addition, PictureSTEM has identified four foundational components of its curriculum that lead to the rich integration of STEM+C and literacy for young students: 1) anchoring the unit within the engineering design process, 2) a realistic and motivating context, 3) high-quality children's literature, and 4) specific and relevant STEM+C concepts and practices (Tank et al., 2018).

As seen in the examples presented here, integrated STEM approaches to introducing engineering to young learners in the classroom can vary in several ways, including the manner and depth that non-engineering disciplines are addressed within a given unit. For example, by expanding the number of lessons connected to the explicit "Learn" step, PictureSTEM can provide more time and space for the exploration of ideas - particularly in mathematics, but also in science - than perhaps is commonly seen within Engineering is Elementary units. In addition, integrated STEM units can leverage stories and children's literature in different ways, such as Engineering is Elementary's approach of developing new stories to set the context for its units, Novel Engineering's use of existing pieces of children's literature to do so, and PictureSTEM's use of a fictional client to set a design context but then also leveraging children's literature to make engaging connections to STEM content and practice.

Given the steady decline of instructional minutes for science in elementary classrooms (Blank, 2013), there can be some who question whether there is space to add engineering into the school day. However, elementary classrooms - many of which are self-contained, meaning one teacher can teach all or most of the subjects - can be ideal venues for introducing engineering as a way to deepen learning of science, mathematics, and literacy when integrated STEM approaches are utilized. Engineering design activities such as those described above can provide a grounding context and purpose for learning about other subjects and disciplines. In addition, integrated curriculum programs like Engineering is Elementary and Novel Engineering are able to use instructional time indicated for both math and reading, due to the connections to those subjects made possible by the design of their lessons.

The current state of STEM integration certainly builds on early work to integrate design activities into science classrooms for older students as a way to deepen the understanding of science concepts. For example, the Design Based Science units (Fortus et al., 2004) for ninth-graders and the Learning by Design units (Kolodner et al., 2003) for middle schoolers effectively leveraged the connected and synergistic processes and content of science and engineering to extend student learning. In the examples presented above, Engineering is Elementary and PictureSTEM both draw on both scientific inquiry practices and scientific concepts to engage students in exploring systems and materials in order to inform their engineering design solutions (Cunningham, 2017; Tank et al., 2018). In so doing, the students apply their scientific skills and knowledge in contextualized and purposeful ways as they generate solution ideas and solve problems, deepening their science learning as they do so.

Engineering Work as Applied Math

While much of pre-college engineering education centers around engineering design, engineering work at the undergraduate level and in professional practice also includes <u>*engineering analysis*</u>. In this work, engineers might not be designing a new product or a new system, but instead analyzing an existing product, and existing process, or an existing system, often to make a decision. For example, an engineer might analyze data collected from an assembly line to identify where more attention is needed or safety procedures need to be revised. This work is typically not as open-ended as design work, but it can still be ill-defined and require problem scoping and problem framing skills (Diefes-Dux & Salim, 2009), and can provide more context to mathematics activities. One specific approach in elementary education is the use of Model Eliciting Activities. Model Eliciting Activities were initially developed by mathematics education researchers to promote mathematical modeling skills (Lesh et al., 2000). However, some engineering education researchers have developed and studied versions that have engineering contexts (e.g. Mousilides & English, 2011). Children are able to learn about the work of engineers and also learn how mathematical modeling can help solve problems to address people’s needs.

Engineering as a Collaborative Activity

Teaming and teamwork is commonly one of a few core topics that introductory undergraduate engineering courses focus on. Some recent research has found that students who had pre-college engineering education experiences that did not emphasize teaming and teamwork had a harder time with the transition to undergraduate engineering studies (Salzman, 2014). At the undergraduate level, students are often introduced to stages of teamwork (e.g. forming, storming, norming, performing, and adjourning, Tuckman, 1965), strategies for working together in a team, and specific team roles (e.g. Facilitator, Timekeeper, Recorder, and Encourager/Gatekeeper)). Teamwork is seen as not only a pedagogical approach for learning, but also as the content and skills to be learned. Additionally, instructors and course designers recognize that students do not learn how to work in teams simply by being placed in teams, but instead through explicit instruction, peer and instructor feedback on teaming skills, and self-reflection (e.g. Loughry et al., 2007).

Similarly, in K-5th grade settings, teamwork and collaboration are not only a pedagogical approach used for engineering education, but are also associated with specific learning outcomes. For example, similar to undergraduate engineering education, in some elementary engineering education curricula children learn about different engineering team roles and have opportunities to practice these roles. In the National Society of Black Engineers' Summer Engineering Experiences for Kids (NSBE SEEK) program, children are assigned roles of "Project Manager, Safety Manager, Materials Manager, Technical Manager, Project Ambassador" as they work on the project activities. In her study of afterschool robotics programs, Leeker observed instances where childrens' engagement in collaboration and teamwork facilitated their problem-solving and critical thinking. For example, working collaboratively was critical for children to troubleshoot as they encountered flaws in the design of their robot. She also observed that the program facilitators and mentors played critical roles in observing how the children were interacting with each other; in this case, teaching collaboration skills to elementary school students meant encouraging children to work together, discussing what it meant to be a good teammate, and then observation and intervention when children were not listening to each others' ideas (Leeker 2020). In another study of K-8th grade students' participation in robotics competitions, Menekse and his colleagues (2015) found that that the level of collaboration quality among team members was significantly associated with the team performance in the robotics tournament.

Students may be willing to work collaboratively while working on engineering activities partially because it is part of the work of engineers, and partially because the nature of engineering design challenges require multiple perspectives and make space for there to be multiple good solutions. Other research has shown that children can engage in rich discourse as they negotiate different solution ideas as well as different ways of understanding the problem (e.g. Silva et al., 2020; Watkins et al., 2014; Wendell, Wright, & Paugh, 2017). Martin (2015) also highlighted collaboration and sharing as critical to engineering and design and contrasted this with the "typically competitive and replicative nature of classroom learning, where the (sometimes tacit) goal is to acquire a set of pre-existing knowledge, and to do so more effectively than one's classmates" (p. 36). Thus while an explicit focus on concepts and skills related to teamwork and collaboration is important for helping children develop teaming and teamwork skills, and for developing an understanding of engineering as a collaborative activity, it is also important to incorporate teamwork as part of the other approaches presented in this paper.

Out-of-School Programs

Historically, universities, nonprofits, and industry have (often collaboratively) developed and offered afterschool or summer programming to introduce engineering to youth and children in response to the lack of inclusion of engineering in K-12 schools. Some of this programming has focused on competitions and robotics (e.g. FIRST Lego Leagues; Welch and Huffman 2014). Leeker (2020) documented the ways that one such program provided opportunities for elementary school aged children to develop critical thinking, troubleshooting, teamwork and communication skills through their participation in the robotics competition program. Other out-of-school programming has focused on using television and websites to educate children, youth, and the public about engineering and engineering design (e.g. DesignSquad, PEEP) (e.g. Linde et al. 2014). Although engineering is now more commonly included in K-12 classrooms, many of these programs continue to be offered, and new programs continue to be developed. For example, in the past 5 years both the Boy Scouts of America and Girl Scouts USA began offering opportunities for children and youth to explore engineering through badgework. Girl Scouts is interested in promoting the participation of girls in STEM, and offers participating scouts opportunities to complete a series of activities to earn badges such as the Mechanical Engineering badge or the Think Like an Engineer journey. Out-of-school time programs often provide opportunities for children to interact with practicing engineers and/or engineering students. Additionally, many offer opportunities for children to connect engineering with their local communities, with their other interests, and/or with their ethnic identities. This is discussed more in question 3.

Some out-of-school time programming also recognizes the important roles that parents, caregivers, and other family members play. For example, many schools host "Family STEM Nights" or "Family Engineering Nights" to allow children and their families to learn engineering concepts and skills together. The Foundation for Family Science and Engineering has developed materials to support this (Jackson et al., 2011). Recent survey findings suggest that parents are interested in seeing their children learn about engineering, but they themselves do not believe they understand what engineering is or how it is different from science (Yun et al., 2010b). Events that include parents and other family members not only allow family members to learn more about engineering, but also allow family members to demonstrate the expertise that they do have and make connections between the engineering activities, family practices, and values.

In her dissertation, Strawhacker (2020) focused on children ages 4-9 and their families as they interact with the CRISPEE tool, a digital tool that "playfully" introduces bioengineering concepts. She found that children who participated at a museum engaged in practices of sequencing, sensemaking, and creative design; for children who participated in sessions during a summer camp, the CRISPEE tool and curriculum supported children's engagement with foundational concepts from bioengineering such as "genes" and "bioluminescence". Further, children engaged with engineering and computer science concepts of hardware, software, and debugging, and bioengineering concepts of ethical consequences of biodesign. Findings reveal new areas of investigation for developing an evidence-based pedagogy of developmentally appropriate bioengineering education for early childhood.

Engineering at Home

Parents and family members support engineering learning in a number of ways; for example, through the attitudes that they communicate about engineering, their encouragement for children to learn about or pursue a career in engineering, their academic support, and the ways they support engineering learning through conversations and activities (Yun et al., 2010a; Dorie et al., 2014). The Head Start on Engineering project, described above, invites parents and children to engage in engineering activities together within the home setting as a pathway to developing engineering interest at the family level (Pattison et al., 2020). In another study, parents with engineering backgrounds reported using a variety of strategies to support their own children in learning engineering knowledge, skills, discourse, and epistemologies: through conversations, books, television shows, movies, toys, puzzles, engaging in engineering-related events, and visits to science centers (Zhang & Cardella, 2010; Dorie & Cardella, 2013). While that study focused on parents with backgrounds in engineering, later studies using surveys found that parents without engineering backgrounds employ many of those same strategies (Yun et al., 2010b). Regardless of their own educational and professional background, parents and family members are critical partners in pre-college engineering education.

Engineering at Science Centers

Finally, science center exhibits, programs, and activities can be rich sites for K-5th grade engineering education (Svarovsky, 2014; Svarovsky et al., 2018). Some exhibits focus mostly on engineering artifacts, while others communicate engineering stories, and others include engineering activities for children to engage in. For example, Designing Our World (DOW) was a four-year, NSF-funded initiative in which the Oregon Museum of Science and Industry (OMSI) and other project partners sought to promote girls' pursuit of engineering careers through community-based programming, exhibition development, and identity research (Johnson et al., 2014). The exhibition included hands-on, interactive elements designed to communicate a vision of engineering as a creative endeavor that contributes to various aspects of daily life. The exhibit interactives engage visitors in design challenges set in relevant, real-world contexts, such as designing a city to manage rain runoff using bioswales and other strategies (Garibay Group, 2017). The OMSI team is currently extending this work by conducting additional research on exhibit design features and staff facilitation strategies that support engineering design through the NSF-funded Designing Our Tomorrow Project (DRL-1811617).

The Maker Movement, sometimes described as a community of practice for creative DIY hobbyists, crafters, and tinkerers (Svarovsky, Bequette, et al., 2017), has provided several new opportunities for young people to engage in creative activity that can sometimes - but not always - resemble engineering and access engineering design practices (Heiman et al., 2017; Martin, 2015). With the swell of interest in the Maker Movement that began during the late 2000s, many science centers and children's museums created dedicated *makerspaces*: areas on the museum floor that allow visitors to engage in using real tools and real materials to create. The types of tools and materials within makerspaces vary greatly, as do the types of activities that are emphasized (Svarovsky, 2019). For example, some makerspaces emphasize using everyday, often recycled, materials while others focus more on electronic, digital, and computational components. Dedicated makerspaces, such as the *Tinkering Studio* at the Exploratorium in San Francisco or the *Creativity Jam and Studio* at the Minnesota Children's Museum, typically house several plain worktables, benches, and a multitude of materials and kits at the ready to support making activities, ranging from superhero masks to giant cardboard structures to wearable electronics. These spaces are most commonly facilitated by museum staff or volunteers, and visitors frequently spend extended amounts of time exploring and creating within these environments (Bevan, 2016; Honey & Kanter, 2013; NRC, 2009b; Sheridan et al., 2014).

Although a more thorough and nuanced discussion of how making and engineering intersect is beyond the scope of this paper, a brief examination of the overlap between making and engineering may be useful. Heiman and colleagues (2015) asked groups of both makers and engineers to describe and define both making and engineering; the results of the study suggest that making is perceived to be more *informal*, *trial-and-error based*, *personal*, and *hands-on*, while engineering is perceived to be more *structured*, *technical*, and engaged with *theories* and *mathematics*. Another approach to exploring the relationship between engineering and making is to utilize the theoretical construct of an *epistemic frame* (Shaffer, 2004; 2006a; 2006b), which - for a particular community of practice such as engineering (Svarovsky, 2011) or making - describes the specific skills, knowledge, identity, values, and epistemology relevant to that community. These frame elements, bound together in particular ways and patterns, comprise the grammar of a particular community and organize the ways in which the members of that community engage in their day-to-day activity. Different communities of practice have different cultures and, as a result, have different epistemic frames. Thus, while making and engineering may draw on similar skills and knowledge, the ways in which those ideas and practices are woven together to form an identity as a maker or an engineer, the ways different artifacts or actions are valued, and the ways that makers and engineers justify their final designs as complete or optimal will often be different.

A concrete example of this is the way that constraints within a design space are defined and addressed within making and engineering experiences; for makers, often the constraints of their designs originate from their own personal preferences (e.g., *I want to make this artifact look a particular way*) while for engineers, constraints are often defined by external stakeholders (e.g. *the community or clients require the design to function in a particular way*). Another example is the way that makers and engineers test and evaluate their designs; makers can be more informal, fluid, and spontaneous with their design testing, using the trial-and-error approach, while engineers are required to be more formal and planful in their design testing, often testing specific *design hypotheses* or perhaps *testing to failure* in order to understand the range and limits of their current iteration. Despite these differences, children engaged in making can often engage in elements of engineering design (Martin, 2015), thereby positioning making as another potential opportunity for young people to learn about engineering.

C. Question 3: How are these approaches consistent or different across grade bands? How are these approaches differentiated to engage students who are typically underrepresented in science and engineering (e.g., students of color, students living in high poverty, English Learners, students who vary in learning)?

Differentiation Across Grade Bands

While many of the core approaches to pre-college engineering education are consistent across grade bands, there are some differences in the specific details of how they are implemented. As noted above, context and narratives are an important part of engineering design. However, the way that texts are presented and the way children engage with the texts can vary -- the activity and narrative may be presented as a series of images or may be presented as text for an adult to read to young learners, while 3rd-5th graders may read longer narratives (or entire books) to learn about the context of the design activity. Additionally, curricula such as Engineering is Elementary (Box 3), Novel Engineering (Box 4), and PictureSTEM (Box 5) are aligned with national standards (NGSS and Common Core).

Based on their work researching and developing EiE, Cunningham et al., (2018), articulated a framework for thinking about how elements of engineering design can be differentiated across three age bands (ages 3-4, ages 5-6, and ages 7-8) when creating curriculum. For example, when conceptualizing a design challenge for 3-4 year olds, the potential design solutions to the challenge should be something that the young learners have used before and might be asked to modify; the solution they are designing should be something that is functional and can be an avenue to imaginative play; and the materials should not be overwhelming to the children in terms of number or complexity. For ages 5-6, potential solutions to the design challenge can be something they have seen or heard about, but does not have to be something they themselves have used before; while for ages 7-8, the potential solutions can be something completely new and unfamiliar to the students. Similarly, the number and complexity of materials can increase as students increase in age, as well as the ways in which students explore materials and balance design constraints. Cunningham et al., (2018) present these trajectories for eight different curriculum design parameters, including setting the application of science and mathematics - where they suggest incorporating relevant content and practice as defined by disciplinary educational standards and applying them meaningfully within the engineering design process.

Students who are Typically Underrepresented in Engineering

Much of the work presented in earlier sections was motivated by concern for broadening participation in engineering and commitment to equity. For example, in a 2016 article Cunningham and LaChapelle reflected on the commitments to equity that motivated and influenced the development of the Engineering is Elementary curriculum when they began in 2003, and the research since then that suggests that “the materials are engaging for girls, children of color, children from low socioeconomic groups, and children with disabilities and have resulted in learning gains related to both engineering and science (Lachapelle, Cunningham, Jocz, Kay, Phadnis et al., 2011; Weis & Banilower, 2010).” In their essay on equity concerns related to making, Vossoughi, Hooper and Escude (2016) differentiate between programs focused primarily on access and inclusion, rather than “critical examination and potential reorganization of the activities and pedagogies themselves.” While some of the work of preK-5 engineering has focused more on access and inclusion rather than critical consideration of the activities and pedagogies of preK-5 engineering, there are many examples of curricula and programs that in introducing engineering disrupt narratives of what engineering is and who can be an engineer, and intentionally and explicitly shift preK-5th grade pedagogical practices (and not only for STEM). Most frequently the narratives that engineering is only for people who are good at math, or only people who are “really smart,” are disrupted by introducing engineering in preK-5th grade to all students (not just those in gifted and talented education programs). Research has also shown shifts in children’s perceptions of engineers in terms of gender, where after engaging in engineering activities in elementary schools children are more likely to see engineering as including women and girls (e.g. Marasco and Behjat 2014); this may be in part because elementary school teachers are predominantly women. Later in this section we describe more limited examples of programs that provide counternarratives affirming the participation of BIPOC children and people in engineering.

In earlier sections we described the importance of context for children to develop problem scoping skills and to practice thinking and working through complex, ill-defined activities. The inclusion of a context can help children think about human (or other user) needs as they develop solutions, allowing them to understand engineering design as a human-centered activity. However, the inclusion of context also allows children to understand engineering as a socially-relevant field, profession, and activity. This attention to addressing human, animal, or environmental needs aligns with the interests and values of many groups of students who are typically underrepresented in engineering (NAE, 2008; Hira et al., 2017). While design contexts are sometimes based in stories or books, they are sometimes situated in communities and children's local contexts - a need present in their classroom or at their school, or a need based on their experience at home. Connecting engineering to children's own communities and own needs further allows them to participate in a learning experience that values their community and their perspectives (e.g. Calabrese Barton & Tan, 2018).

The next sections describe approaches to addressing the specific needs and strengths of specific groups that are underserved: students who are BIPOC, girls, students living in high poverty, English learners, and students who vary in learning. Recently attention has also been given to the needs and strengths of rural learners, but more so at the high school level. Similarly, we do not discuss approaches that specifically consider nonbinary or LGBTQIA+ children, as there is a paucity of work in this area for preK-5th grade.

Girls

The participation of women and girls in engineering has been a persistent concern for decades, and yet women still make up only 20.9% of undergraduate engineering students and 13.9% of practicing engineers (NSF, 2019). The Society for Women Engineers and the Women in Engineering ProActive Network and programs at individual universities (typically women in engineering programs) are actively engaged in developing strategies, materials and programming to engage girls in engineering activities. These activities align with recent research in two major ways: they often incorporate socially-relevant activities (Dorie et al., 2015; NAE, 2008; Svarovsky, Cardella, et al., 2017) and include female engineers or female engineering students as activity facilitators and presenters (Kekelis et al., 2014). As noted earlier, Girl Scouts of America also develops engineering programming and activities specifically for girls. This programming is sometimes offered as events facilitated by a Women in Engineering program or other university-based engineering entities (e.g. Jovanovic et al., 2019). At other times the programming is incorporated in a troop meeting by the volunteer troop leader. New research that is currently underway at the Ohio State University is beginning to explore how Girl Scout badge activities may impact the engineering identity development of the experiences of middle-school aged girls (Clark, 2019), which could inform similar future research on elementary-school aged girls.

Another recent strategy has been the development of engineering-related toys that are specifically for girls. Goldieblox and Roominate sets were both developed by women who studied engineering and wanted to see more girls engaged in engineering and engineering-related learning. There is some evidence to suggest that engineering-related toys and kits are purchased for boys nearly twice as often as they are for girls (Inman & Cardella 2015; Shoaib & Cardella, 2020). Products that are specifically designed and marketed for girls have the potential to shift this trend in play experience, but it is not yet clear if these toys are having an impact.

Students who are BIPOC

Many universities have offices or programs that are charged with developing and implementing programming and services to improve the recruitment and retention of students of color in engineering. These programs support undergraduates (Lee & Matusovich, 2016) but also administer a variety of programs for pre-college students. While there is an implicit hope that the pre-college programs will lead to the recruitment of Black, Latinx, Indigenous, and other People of Color to that university's undergraduate engineering programs, many of these pre-college programs are designed to more broadly introduce children to engineering and introduce children to engineers who are people of color. These offices and programs are typically staffed by engineers and educators who are themselves people of color, and undergraduates are often employed to run the outreach events and activities (e.g. Gaskins et al., 2019).

The "Summer Engineering Experiences for Kids" program was initially developed by the National Society of Black Engineers in 2007 and is currently offered in 12-16 different cities across the US each year. This 3-week program was designed by Black engineers (undergraduates and practicing professionals) for Black and Latinx children, where the program activities are facilitated by undergraduate engineering students and in-service teachers who are also Black and Latinx. The camps meet in classrooms at schools that serve students who are economically disadvantaged. Classroom posters have been developed for the program that feature images (both graphics and photographs) of Black and Latinx children and practicing engineers. Research and evaluation of the camps have captured positive impacts for both the children who participate and the undergraduates and teachers who facilitate the camps (Fletcher et al., 2017; Young et al., 2017; Edwards et al., 2018; Lewis et al., 2018; Leeker et al., 2019). Additionally, some camps are designed specifically for Black and Lantix girls, and in her dissertation research, Fletcher (2017) investigated the differences in outcomes for girls who participated in either co-ed or all-girl camps.

Recently NSBE also began hosting a "STEAMfest" event for pre-college students of all ages as part of their annual Convention. Participating in the STEAM event allows children to engage in a variety of short engineering activities, hosted by different universities, non-profits, and local companies, while also participating in the larger NSBE Convention, typically attended by more than 10,000 aspiring and practicing engineers, educators, and representatives of more than 250 academic institutions, government agencies, corporations, and nonprofit organizations. The majority of the convention attendees are Black, allowing children attendees to see and interact with thousands of engineers and engineering students who look like them.

Fewer studies exist that document strategies used specifically for Latinx or Indigenous children. We did not find any research on strategies used specifically for elementary aged

Latinx children. However, in his dissertation work, Alex Mejia investigated the funds of knowledge of Latino and Latina high school adolescents, and how they used their funds of knowledge to solve engineering design problems in their communities, with a goal of generating a framework that teachers can draw from in order to create culturally responsive high school engineering instruction that connects adolescents' out-of-school practices to the formal practices of engineering (2014). Tzou and colleagues (2019) designed, implemented, and explored a set of workshops for Indigenous families that integrated design, storytelling, and robotics while centering Indigenous ways of knowing and being. This important work presents a vision of the possible for engineering education and STEM education more broadly, including how empowering families and youth through educational experiences can be restorative and powerful.

Specific to young learners, in response to Question 1 it was noted that while play is often cited as an effective approach to supporting STEM learning for young learners (e.g. Yogman et al., 2018), play is not a concept that is universally shared or valued across communities (Gaskins, 2008; Rogoff, 2014; Shirilla & Golinkoff, 2019). Other approaches may be equally if not more effective for supporting children learning and development in other cultural contexts (Alcalá et al., 2018; Wang et al., 2020).

Additionally, as previously noted in the Essential Considerations and in Question 1, too often there is an assumption that families, and in particular families from some communities, are deficient in their engineering knowledge and practices and do not have a role to play in engineering learning systems. Some studies are beginning to document the rich engineering-related knowledge, skills, and practices within Black (Tolbert, Jones and Cardella, under review) families, underscoring the need for educators to better understand, connect with, and build on these funds of knowledge (González et al., 2005) to not only support more equitable engineering education but also expand and enrich conceptualizations of engineering more broadly. In their study, Tolbert and her colleagues share middle-school-aged youth and their parents' reflections on the practices that the families engaged in as the youth were elementary school and middle school aged. Several parents shared reflections on their child's evolving interests, which included both STEM-related interests and other interests; for example, interests in physics as well music and the arts. Parents talked with their children about career pathways that combined these different interests. Another family shared their experience with creating a family culture of repairing, tinkering and creating, where the children had the freedom to work on projects around the house and parents provided resources and opportunities to develop skills. In this family, children help each other with their projects and also get help from their father who is a scientist who models inquisitiveness for his children (Tolbert, Jones and Cardella, under review).

Students Living in High Poverty

As discussed in response to Question 1, Spanish- and English-speaking families from low-income communities find resourceful ways to integrate engineering into ongoing family learning experiences despite challenges. Important barriers these families face include lack of engineering-related learning experiences, costs associated with existing programs and resources, life challenges connected with poverty, and racism and cultural barriers within the education system. Programs like Head Start on Engineering have been designed with these needs in mind, as well as the recognition of the assets that these families bring.

Another consideration that has been integrated into approaches used with students living in high poverty is avoiding the use of food as construction materials in engineering design activities. While spaghetti noodle and mini-marshmallow bridges have become a popular short activity used to introduce engineering design, the use of food in this activity is not sensitive to the food insecurity that children living in poverty may be experiencing.

Other approaches to serving children living in poverty have similarly focused on the materials involved in project work, where researchers and activity developers have centered using everyday and low-cost materials so that families and schools could adopt and implement activities, and have considered strategies for attending to families' transportation needs.

Finally, some recent research has found that engineering activities can provide new opportunities for children living in high poverty to demonstrate their abilities. For example, in their article, Robinson and her colleagues (2018) discuss alignment between the needs and preferences of students from low-income households for hands-on design experiences and the types of experiences that are afforded by engineering and engineering design, and how this alignment affords new opportunities for teachers and counselors to identify and develop talent.

English Learners

While some approaches to preK-5th grade engineering education have recognized linguistic diversity by translating materials into Spanish, other efforts have addressed the needs and recognized the strengths of English learners more holistically. For example, Cunningham and Lachapelle (2014) outline a set of inclusive curriculum design principles for engineering, grouped into four main categories: setting learning in a real-world context, presenting design challenges that are authentic to engineering practice, scaffolding student work, and demonstrating that "everyone engineers" and everyone *can* engineer. Evidence of extended and ongoing student engagement with English language learners was also presented, showing how students were engaged by the design process and problem solving involved with the engineering activities long after the original unit was taught in their class.

In other cases, researchers have conducted research on English Learners' experiences with elementary engineering education, which also provides some information about the ways English learners engage with engineering. For example, Pantoya and Aguirre-Munoz (2017) studied linguistically diverse K-2nd grade aged students' experiences with *Engineering is Elementary* and complementary engineering-related activities, with a focus on academic conversations. Three of the four schools participating in the study "had 80%-90% of the student population classified as Hispanic, in these schools ELLs represented 30%-50% of the student population" (p. 6). The investigators compared students who participated in the EiE and other engineering activities vs. students who did not, and found significant results with low to moderate effect sizes; children who participated in the engineering activities showed slightly higher knowledge means on (1) an Engineering Design Assessment and (2) a Technology Assessment.

Students Who Vary in Learning

In this section, we consider three groups of students: students who "vary in learning" because they are seen by educators as being less academically successful than their peers; students who are recognized as "gifted", and students who are neurodiverse. Initially, some research amongst middle-school students presented findings that engineering learning experiences could help educators as well as students redefine "who" is academically successful, where students who previously were seen as "underperformers" in math and science were able to demonstrate math and science ability in new ways through engineering design (Silk et al. 2009). More recently, researchers have documented similar findings in fourth and fifth grade classrooms, where "many students in all research settings identified 'smart engineers' in their class differently (more broadly) than they defined 'smart students' (those students who were smart in normal school activities), an indication that engineering has the potential to disrupt status quo cultural meanings of 'smart'." (Hegedus et al., 2014, p. 6).

Finally, students who vary in learning have become a focus for preK-5th grade engineering education only very recently, and few studies have been published to date. In her dissertation study of the experiences of children with high-functioning autism, Ehsan (2020) found that the 10-year-olds in her study engaged in engineering design activities and an iterative design process much like a typically developing child would. Other research suggests that the way teaming and teamwork are incorporated in engineering activities should be carefully considered for children on the autism spectrum, because they experience challenges with empathizing skills such as social communication and interaction (Baron-Cohen, 2009). In her study, Ehsan noted that while the children did not socially interact with their family members who were also part of the study session, the parents played important roles in supporting the children's engagement in design.

D. Question 4: How does engagement in engineering impact other learning outcomes (e.g., science, mathematics, English Language Arts, computational thinking) in the early childhood and elementary grades?

Currently, there is limited research that speaks to how incorporating engineering into early learning contexts and elementary classrooms can impact learning outcomes in other disciplines with most of the extant literature focused on exploring science learning through engaging in engineering activities. The largest study to date was conducted by Cunningham and colleagues (2019), who used a cluster randomized control trial in over 600 classrooms to examine the efficacy of the Engineering is Elementary curriculum. Results demonstrate that students exposed to the EiE curriculum outperformed students exposed to the control curriculum in both engineering and science learning outcomes. In addition, the difference between groups was greater for science learning than for engineering learning, suggesting that making meaningful connections between science content and practice and engineering design can deepen disciplinary learning in science.

Although smaller in scope, other studies also support the claim that engineering can deepen science learning for elementary students. Yoon et al. (2014) examined 2nd, 3rd, and 4th grade students' learning after an integrated STEM experience, and found learning gains in science when compared to a control group. Wendell and Rogers (2013) found that third- and fourth-grade students' changes in science learning as connected to engineering design experiences using LEGO Engineering activities were greater than those for students who engaged in the school or district-selected science curriculum. In a study of 4th - 8th graders engaging in engineering activities, Selcen Guzey and colleagues (2017) found some evidence of students participating in engineering as having a positive effect on their science learning, but only for topics in physical science and not in life science, which is a finding also supported by an evaluation study for Engineering is Elementary (Lachapelle et al., 2011).

Clearly, investigating the learning outcomes for early learners and elementary students for other domains beyond engineering as a result of engaging in engineering activity is an area for future research. Current research on learning outcomes for engineering activities with young learners is focused on developing new ways to measure (Purzer & Douglas, 2018) and observe (Bagiati & Evangelou, 2018) engineering learning; teachers' perspectives on engineering learning for their elementary students (Pleasants et al., 2019), and how engineering learning can be impacted by the instructional practices, preparation, and self-efficacy of teachers (Cunningham et al., 2020; Guzey & Aranda, 2017; Lie, Guzey, & Moore, 2019).

E. Question 5: How does engagement in engineering shape students' identities and interests?

Interest and identity are complex, interrelated constructs, both of which are theorized and operationalized in a variety of ways by researchers and educators. Identity in particular has a complex history (Bell et al., 2018; Simpson & Bouhafa, 2020), including ongoing debates about the relative importance of studying identity as a relatively static and measurable characteristic of an individual (e.g., Avraamidou, 2020; Dou & Cian, 2020) or identity as a dynamic, context-specific component of how individuals negotiate who they are through interactions with others (e.g., Chappell & Varelas, 2019; Pattison, Gontan, et al., 2020). In this paper, we do not take up these nuances, although we acknowledge their importance. Broadly, we are interested in the ways that current research sheds light on how children and the significant adults in their lives are motivated to engage (and re-engage) with activities, topics, and experiences related to engineering and how this motivation shapes and is shaped by how individuals see themselves and are seen by others. Some researchers working in this area have focused on interests and identities related to engineering as a field and career, and whether children can see themselves or people like them as an engineer (e.g., Capobianco et al., 2012, 2015), while others have focused on engineering as a set of related problem-solving practices, skills, and mindsets and how children see themselves as doers of engineering activities (e.g., Jung & McFadden, 2018; Nazar et al., 2019; Pattison et al., 2018). While the body of research on how preK-5th grade aged children's engagement in engineering shapes their identities and interests is small, emerging research indicates that preschool- and elementary-age children do demonstrate strong and persistent STEM-related interests, that these interests vary across children and are malleable, and that early interests have implications for long-term STEM engagement and achievement

(Alexander et al., 2012; Crowley et al., 2015; DeLoache et al., 2007; Fisher et al., 2012; Gottfried et al., 2016; Hecht et al., 2019; Maltese et al., 2014; Neitzel et al., 2017).

Interests

Many approaches to preK-5th engineering education have focused on increasing students' interest in engineering, often by trying to create experiences that are interesting to children based on opportunities to interact with activities, objects, and people. Recent work from Hynes and his colleagues posits that these experiences that are designed to promote situational interest (Krapp et al., 1992) may only lead to fleeting interest in engineering, while experiences that are designed to allow children to see connections between their own personal interests and engineering might be more likely to predict prolonged and persistent engagement in engineering (Hynes and Maxey, 2018). Hynes' *Make an Engineer* is one activity designed with this in mind: children are encouraged to think about the types of problems they are interested in solving, list two of their own personal interests, and select an engineering habit of mind that they could use to address their problem (Hynes, Beebe, Hira & Maxey, 2018).

To further investigate children's interests related to engineering, Hynes and his team developed the "Fit of Personal Interests and Perceptions of Engineering" instrument (Hynes & Maxey, 2018). When used in partnership with the National Society of Black Engineers during their Summer Engineering Experiences for Kids program for children who have just completed 3rd-5th grade, the survey showed that by the end of the three-week camp, there was more alignment between the students' own interests & their perceptions of engineering, where one of the most notable shifts was that by the end of the camp they had a more positive view of engineering as involving artistic elements, and engineering as a social endeavor.

Identity

The Engineering Identity Development Scale was developed based on Gee's identity framework (2001) to uncover, evaluate, and explain the multiple and diverse factors that contribute to young students' (1st-5th grade) engineering identity formation (Capobianco et al., 2012). The assessment consists of academic identity, school identity, occupational identity, and engineering aspiration items. The instrument has been used in many different studies of elementary engineering education (e.g. Cardella et al., 2019), with generally consistent findings of pre-/post-test gains after children have participated in engineering activities (whether at school or through out-of-school-time programming).

While the Engineering Identity Development Scale measures children's engineering identity through Likert Scale items, other researchers have investigated how children see themselves in relation to engineering through writing, drawing and talking about who engineers are and what engineers do. Many researchers have used the Draw an Engineering Test (e.g. Cunningham & Knight, 2004; Oware, 2008; Weber et al., 2010) (also at times referred to as the "Draw an Engineer Task") to investigate children's perceptions of engineering and engineers. In multiple studies, researchers saw that the post- drawings included representations of engineering that were more consistent with the work of engineers, but also more drawings of females. When the task was administered during the SEEK camp, several children drew pictures of Black engineers (Lightner et al., 2020). While the Draw an Engineer Task elicits children's perceptions of engineers and engineering, it does not ask children about whether they see themselves as doing engineering or otherwise having an engineer identity; coupling the task with an interview can allow children to consider and construct a multimodal identity narrative (Tucker-Raymond et al., 2007). In other research, a version of the Draw an Engineering Task was used to look at how teachers' identities shift as they become "teachers of engineering" (Hammack et al., 2019).

Young Children

For young children, it may be more productive to think of interest and identity as a family-level phenomenon, since developmental processes are highly reciprocal between adults and children at this age and many of the components that have been theorized for these constructs are likely distributed across family members. Preliminary results through the Head Start on Engineering project suggest that families can develop long-term interests and identities related to engineering but that these interest "pathways" may look very different across families, depending on their values, prior interests, life experiences, etc., and may not conform to a more academic- or school-oriented conceptualizations of engineering (Pattison, Svarovsky, Ramos Montañez, Gontan, et al., 2020; Pattison & Ramos Montañez, 2020). The HSE project and other studies have also highlighted the existing practices, knowledge, and resources within families related to engineering that may go overlooked by educators or may not be explicitly connected to engineering (Cardella, 2020; McWayne et al., 2018; Pattison & Ramos Montañez, 2020; Svarovsky, Pattison, et al., 2017; Tõugu et al., 2017). Finally, for young children, it is not clear at this point if efforts to support engineering-related interests and identities at this age should focus on engineering practices, engineering as a career, or both.

Identity as Evolving and Multi-faceted

Much of the work to date on identity and interest has focused on measuring changes in interest and/or identity rather than exploring how children develop engineering-related identity and interest. The studies that do explore identity as something that evolves over time have primarily focused on older children. For example, research on the engineering-focused Designing Our World project at the Oregon Museum of Science and Industry focused on 9-14 year-old girls. The study highlighted the importance of acknowledging identity as something that is constructed and negotiated within specific settings and groups (Pattison, Gontan, et al. 2018; Pattison, Gontan, et al. 2020). Similarly, Tan and Calabrese Barton's study (2018) of 10-15 year olds' experiences in two makerspaces provide rich descriptions of how children draw from their different identities (e.g. as a Black girl and as a sometimes homeless youth) as they design and create. Finally, in their study of urban elementary school students, Wright, Wendell and Paugh (2017) investigated students' emergent engineering identities in terms of how students saw themselves as doers of engineering, and found that students' views involved risk management in collaborative decision making; being a doer of engineering "revolved around their ability to avoid trouble and… meant being able to collectively develop a team solution while also avoiding the potential risks of being reprimanded by the teacher or alienating teammates" (p. 285).

F. Question 6: What professional learning opportunities (including initial teacher education and ongoing professional development), or other supports/structures (e.g., curriculum materials, school leaders) help early childhood and elementary teachers effectively integrate engineering design into a range of learning experiences, including science and mathematics instruction?

Over the past 20 years, as interest in advancing engineering awareness and learning for younger students has been on the rise, a somewhat unique professional development challenge began to emerge. Unlike the disciplines of math and science, which have at least some amount of required coursework within the pre-college setting for some time, the vast majority of preK-12 educators have had little to no exposure to engineering education themselves (Brophy et al., 2008); unless they had taken a course on engineering, most likely at the undergraduate level. As such, engineering-focused professional development for in-service elementary teachers quickly became identified as an urgent need.

At present, there are a wide range of options for elementary in-service teachers to engage in professional development aimed at introducing engineering to their classrooms. Perhaps the most common model is the in-person workshop, ranging in length anywhere from a one-hour session to a multi-day (or even multi-week) program. As mentioned in Box 3 above, Engineering is Elementary recognized the need for comprehensive professional development early on (Cunningham et al., 2006), and went on to develop a series of EiE training workshops focused on introducing teachers to definitions of engineering and technology, the engineering design process, and the four-lesson structure of their units. The workshops leverage many of the effective principles for professional development (Darling-Hammond et al., 2017; Desimone, 2011), engaging teachers as active learners in engineering activities, providing opportunities for reflection, modeling effective practice, and drawing on the lived experiences of teachers throughout the session. EiE also created a “Train-the-trainer” professional development series, where teachers could engage in a 3-5 day experience to deepen their own understanding of engineering and the use of the EiE curriculum, and then could train other teachers at their school or within their district. EiE went on to develop a national network of certified professional development providers to extend the reach of their workshops across the country (Sargianis et al., 2012).

Universities, particularly those that house engineering or STEM education centers, also provide a number of professional development opportunities for elementary teachers. The INSPIRE Research Institute for Pre-College Engineering at Purdue University has offered professional development for preK-4th grade teachers and informal educators focused on integrated STEM, leveraging institute faculty and research projects to provide an introduction to using engineering in the early childhood/early elementary classroom (e.g. Duncan et al., 2011). Similar programs were also offered for teachers in grades 3-6 at the University of Minnesota (Guzey et al., 2014). The Tufts Center for Engineering Education Outreach (CEEO) offers week-long workshops open to elementary educators, which both draws on and contributes to advancing the research on engineering-focused teacher professional development (Watkins et al., 2018). The CEEO also offers online training for K-12 educators, which provides flexibility and can increase access for educators, as well as a teaching certificate program through its Teacher Engineering Education Program. The Center for STEM Education at the University of Notre Dame provides an extended opportunity for elementary teachers to deepen their understanding and practice of integrated STEM, through their 2.5-year STEM Teaching Fellowship program that seeks to form equity-focused STEM Teacher Leaders (Trinter et al., 2020). While typically focusing on middle- and high-school teachers, Research Experiences for Teachers (RETs) are available at many research universities, and a few programs focus specifically on providing opportunities for elementary school teachers to participate in engineering research while also learning approaches for teaching engineering & developing engineering curricular materials.

Organizations and research projects focused on informal learning, such as museums and community partnerships, also offer professional development opportunities for early childhood educators and elementary teachers. Engaged as part of the EiE professional development network, the Museum of Science in Boston, the Science Museum of Minnesota, and the Arizona Science Center all offer several sessions and levels of EiE training for elementary teachers. The Lawrence Hall of Science in Berkeley, CA, has designed multiple teacher professional development programs that integrate science, engineering, and ELA standards at the elementary level. The Children's Museum of Pittsburgh, which houses a world-class makerspace for young learners and their families, offers multiple professional development workshops for early childhood educators and elementary teachers. The New York Hall of Science engages educators, both informal and formal, in professional development using its Design-Make-Play framework (Honey & Kanter, 2013) that informs integrated STEM activity. Finally, projects like Head Start on Engineering, which focus on advancing informal family-based STEM learning through community partnerships with early childhood education centers and informal learning institutions, have been developing models for engineering-focused professional development for preschool and pre-kindergarten teachers.

Of course, in-service teacher professional development opportunities only partly address the challenges associated with fully incorporating engineering in preK-5 classrooms. Pre-service teacher education programs can play a key role by including engineering content into science and math education classes for elementary teachers, or perhaps by designing elementary education programs focused on integrated STEM. For example, the National Center for STEM Elementary Education at St. Catherine University in Minnesota is the first teacher training program to have developed a course for pre-service elementary teachers focused on engineering education and also require elementary education majors to complete a STEM certificate before licensure. At the school level, school structures, including schedules, teaching assignments, and decision-making processes can also positively or negatively impact the likelihood and ease of including engineering during the school day. Support, or lack thereof, from school and district leaders to implement engineering activities for students can also be an extremely influential factor, particularly when considering the investment of time and resources that may be required to build capacity for engineering education within their faculty and staff.

G. Question 7: How do policies at the federal, state, or local level constrain or facilitate efforts to teaching and learning engineering in preK- 5th grade?

State and National Curriculum Standards

One of the major drivers for increased inclusion of engineering in K-12 classrooms has been the development and adoption of state and national curriculum standards. While mathematics standards have not included engineering, "technology and engineering have been major features of science standards, starting with publication of *Science for All Americans* by the American Association for the Advancement of Science (AAAS, 1989). *Science for All*

Americans served as the catalyst and model for all subsequent efforts to develop K-12 science standards" and included a chapter focused on the "nature of technology" and ways that new technologies are designed and engineered (Sneider & Purzer, 2014, pp. 4-6). In 2000 the International Technology Education Association (now the International Technology and Engineering Education Association) published *Standards for Technological Literacy*, laying out 20 standards about the nature of technology, the relationship between technology and society, the engineering design process, and key technological systems. These standards provided clarity and granularity, following the publication of the National Science Education Standards (NRC, 1996) that included "an emphasis on (1) the connections between the natural and the designed worlds, and (2) the abilities related to the design process as a complement to the inquiry process" (Sneider & Purzer, 2014, p. 7).

While these standards provided guidance for how engineering might be included in K-12 classrooms, decision-making about what students should learn resides at the local level in school boards, with guidance and support from the state-level. In a 2006 study of state curriculum standards, researchers found that at that time only 18 states included engineering design skills in their state standards (Koehler et al., 2006). Massachusetts was the first state to include "engineering" and "technology" in its state science standards beginning in 2001. The Museum of Science in Boston was an early strong supporter of the new efforts to establish engineering and technology as part of science, and the Museum established the National Center for Technological Literacy in 2004, where *Engineering is Elementary* is one of the most notable products of the center (Sneider & Purzer, 2014). By 2012, six years after Koehler's study, the number of states including engineering, technology, and design in their content standards had grown to 34 - with variation in the amount of emphasis on engineering and design as well as variation in whether engineering was included as part of the science standards, or if engineering/technology were a separate set of standards (Carr et al., 2012). Thus, as the National Research Council was developing *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012), which included chapters on "Practices of Science and Engineering" and "Technology, Engineering, and the Applications of Science," two-thirds of US states already included engineering in their standards. Compared to the 1996 National Science Education Standards, the 2012 Framework provided clarity for distinctions between engineering and technology and elevated the prominence of engineering design. As the *Next Generation Science Standards* (NGSS Lead States, 2013) were developed based on the *Framework*, committee members from across states (with varying existing state standards) collaborated on a set of standards that further elevated the inclusion of engineering in K-12 classrooms. Perhaps more importantly, the *Framework* and the *Next Generation Science Standards* articulated a set of engineering-related concepts and practices that are more consistently recognized across states; even states that have not adopted NGSS have referred to the Framework and NGSS as they developed or refined their own state standards. This allows researchers and curriculum developers to develop NGSS-aligned resources that are relevant to the goals of teachers, schools, and out-of-school-time programming across the nation.

White House and Legislative Initiatives

The Elementary and Secondary Education Act of 2002 (also known as No Child Left Behind) required that states adopt standards and corresponding assessments for mathematics, English, social studies, and science. Although the push for states to adopt standards and assessments for science had the potential to strengthen the inclusion of science and engineering in K-12 classrooms, the stipulations of the Elementary and Secondary Education Act that students be tested every year in English and mathematics (and students needed to demonstrate improvement each year) accomplished the opposite. With the increased pressure to have students perform well on mathematics and English tests, schools began devoting more time to those subjects and a large majority of schools substantially decreased the time spent on science (Center on Education Policy, 2008; Sneider & Purer, 2014), leaving little time to add any additional topics such as engineering. As noted earlier in this paper, educators and curriculum developers have strategically taken an approach towards integrating engineering (and science) with literacy and mathematics in light of the constraints on the school day that are products of this Act. A similar emphasis on mathematics and English, resulting in similar time constraints, exists in many preschool classrooms, leading to similar strategies of integrating engineering with mathematics and English.

In 2011, in his State of the Union address, President Obama issued a call for adding 100,000 excellent STEM teachers to our nation's schools over the coming decade. Many universities as well as other entities focused on STEM education and teacher professional learning were already dedicated to the work of preparing and supporting STEM teachers, but this call raised attention to this need, and led to responses such as the development of the 100Kin10 network. The network emerged in 2011 to coordinate and support the work of institutions across the nation: academic institutions, nonprofits, foundations, companies, and government agencies. The network provides participating organizations opportunities to share their work with each other and learn from each other, and also provides funding opportunities, thus catalyzing development and dissemination of preK-12th grade engineering education resources.

Two other Acts have been introduced in Congress, and referred to the Subcommittee on Early Childhood, Elementary, and Secondary Education. In 2015 Rep. Paul Tonko introduced the Educating Tomorrow's Engineers Act of 2015, which focused on amending earlier Acts to require states to incorporate engineering design skills and practices in their standards and assessments (Educating Tomorrow's Engineers Act, 2015). In 2016, Rep. Tim Ryan introduced the Pre-College Engineering Act, which would "establish a grant program to encourage, through public-private partnerships, the development and implementation by states and local educational agencies of sustainable engineering education programs in elementary and secondary schools. The National Science Foundation (NSF) shall administer the program." (Pre-College Engineering Education Act, 2016). While the Act has not been passed into law, the National Science Foundation continues to support pre-college engineering education through a number of programs across multiple directorates. For example, many of the programs in the Division of Research on Learning in Formal and Informal Settings fund preschool-5th grade engineering education research and development projects, while the Division of Engineering Education and Centers funds pre-college engineering education research and development projects, Research Experience for Teachers programs, and requires multi-university Engineering Research Centers to engage in outreach.

III. KEY CONCLUSIONS

In this section we briefly summarize four key conclusions that are related to PreK-5th grade engineering education.

Pre-College Engineering Education as an Emerging Discipline

Although engineering education has grown broadly as a field over the past century, the past 20 years have seen an increased emphasis on the specific development of pre-college engineering education as a scholarly community, separate from the fields of K-12 science education and math education. Some indications of pre-college engineering education emerging as a distinct field include a dedicated journal (the *Journal of Pre-College Engineering Education Research*) that was established in 2013, a professional society division of approximately 1200 members (the Pre-College Engineering division of the American Society for Engineering Education), and a conference series specifically focused on pre-college engineering education (the *P-12 Engineering and Design Education Research Summit*). While engineering can certainly enhance disciplinary learning in science and mathematics, and be leveraged in service of the cultivation of skills and knowledge in those domains, it is increasingly being included in preK-5 educational settings as a distinct, separate, and intentional disciplinary emphasis. Teachers and informal educators are developing pedagogical content knowledge specific to teaching engineering, and assessments have and continue to be developed to measure change in the understanding of engineering concepts.

Engineering Learning in the Preschool Years

While there continues to be a need for increased attention given to engineering learning for elementary school aged learners, much progress has been made in the past 20 years. More recently, attention has been turned to understanding and supporting engineering learning in the preschool years, including family-based engineering learning experiences. This is an important and growing area of research complementing the work with older children.

Equity, Privilege, and Access

While much of the PreK-5th grade engineering education work that has already been done has been motivated by concerns for equity and access, ensuring that the needs and strengths of learners who are typically underrepresented in engineering (e.g. girls, students of color, students living in high poverty, English learners, and students who vary in learning) are centered continues to be a priority for PreK-5th grade engineering education. The ongoing challenges around the definition of engineering, whose views are privileged and legitimized, and who has access to high quality engineering education opportunities, will remain central to the work of many scholars and researchers in the field who are committed to advancing equity in engineering and engineering education.

Unique and Powerful Opportunities

Finally, this summary of engineering education literature points to several potentially transformative areas for future work, including:

1. The natural connections between engineering design processes and other aspects of development that are critical for young learners (e.g., executive function, mastery motivation, socioemotional learning, and theory of mind).
2. The potential of using the engineering design process to support learners from traditionally underserved communities in identifying, understanding, and solving problems in school, work, and life. This will require ongoing discussion of how

engineering is defined and collaboration with communities to democratize approaches to engineering education.

3. The broader impacts of situating engineering design activities for young learners within socially relevant/social justice contexts as a way to build empathy and civic engagement.

Over the last several decades, engineering has emerged as its own important and independent domain within the STEM education field. The growing body of research outlined in this paper provides initial guidance for researchers and educators focused on engineering learning in early childhood and elementary education. However, many questions remain; and more work is needed to connect the different sub-communities of people engaged in this work. Given the momentous challenges facing our society at every level, now more than ever it is imperative that children and adults possess the engineering skills and mindsets to be effective, empathetic, and resilient in identifying, understanding, and solving problems. It is also essential that the solutions that professional engineers develop over the next several decades reflect the needs, interests, and values of every community within this country. An ongoing and deepened commitment to engineering education research and development for preK-5th grade aged children is a critical step to addressing these long-term goals.

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